Cardiovascular Research (2015) **105**, 213–222
doi:10.1093/cvr/cvu257

Dissecting abdominal aortic aneurysm in Ang II-infused mice: suprarenal branch ruptures and apparent luminal dilatation

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Received 6 August 2014; revised 1 December 2014; accepted 1 December 2014; online publish-ahead-of-print 23 December 2014

Time for primary review: 41 days

Aims In this work, we provide novel insight into the morphology of dissecting abdominal aortic aneurysms in angiotensin II-infused mice. We demonstrate why they exhibit a large variation in shape and, unlike their human counterparts, are located suprarenally rather than infrarenally.

Methods and results We combined synchrotron-based, ultra-high resolution *ex vivo* imaging (phase contrast X-Ray tomographic microscopy) with *in vivo* imaging (high-frequency ultrasound and contrast-enhanced micro-CT) and image-guided histology. In all mice, we observed a tear in the tunica media of the abdominal aorta near the ostium of the celiac artery. Independently we found that, unlike the gradual luminal expansion typical for human aneurysms, the outer diameter increase of angiotensin II-induced dissecting aneurysms in mice was related to one or several intramural haematomas. These were caused by ruptures of the tunica media near the ostium of small suprarenal side branches, which had never been detected by the established small animal imaging techniques. The tear near the celiac artery led to apparent luminal dilatation, while the intramural haematoma led to a dissection of the tunica adventitia on the left suprarenal side of the aorta. The number of ruptured branches was higher in those aneurysms that extended into the thoracic aorta, which explained the observed variability in aneurysm shape.

Conclusion Our results are the first to describe apparent luminal dilatation, suprarenal branch ruptures, and intramural haematoma formation in dissecting abdominal aortic aneurysms in mice. Moreover, we validate and demonstrate the vast potential of phase contrast X-ray tomographic microscopy in cardiovascular small animal applications.

Keywords Abdominal aortic aneurysm • X-ray CT • Grating interferometry • Angiotensin II • Mouse model

1. Introduction

Abdominal aortic aneurysm (AAA) occurs in 5–9% of the population over the age of 65 years,[1] and transmural aneurysm rupture is the 10th cause of death in the industrialized world.[2] AAA can be induced by the infusion of angiotensin II in hypercholesterolaemic mice,[3–6] which leads to relatively stable AAA,[7] or by a combined infusion of angiotensin II and anti-TGF-β antibodies in normolipidaemic mice,[8] which leads to more rupture-prone AAA.[9] Angiotensin II-infused mice form the basis of most preclinical pharmacological aneurysm research.[10–15]

According to literature, the early phase of angiotensin-II infusion is characterized by macrophage infiltration, medial elastolysis, luminal expansion, and thrombus formation.[3,4,6,7] All these characteristics are also present in human AAA,[16] yet important patho-morphological differences exist between mice and men.[17] In mice, the AAA (i) develops suprarenally rather than infrarenally,[3,5] (ii) shows sudden rather than slowly progressing luminal dilatation,[4,6] and (iii) presents intramural rather than intraluminal thrombus.[18] For this reason, in the current manuscript, the term 'dissecting AAA'[18] was preferred over the more commonly used 'AAA'. A large variability within murine dissecting

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AAA shapes has been reported, classified from Grade I (dilated suprarenal lumen without thrombus) over Grades II and III (remodelled tissue with/without thrombus, often located eccentrically on the left side of the suprarenal aorta) to Grade IV (polymorphic AAA with multiple aneurysms along the suprarenal and thoracic aorta).[5,12] These morphological differences have been reported by different laboratories and in different mouse models but have never been fully explained. We hypothesized that better imaging techniques, visualizing the aortic wall at an ultra-high resolution and in 3D, might allow us to understand which processes lead to the macroscopically observed phenomena.

An accurate morphologic evaluation at microscopic level can be achieved through histopathology, but this relies on two-dimensional sections that make 3D reconstruction and analysis challenging if not impossible.[18] *In vitro* (vascular casting) as well as *in vivo* (contrast enhanced) micro-CT offer an isotropic pixel size up to 50 μm but are restricted to the blood-filled aortic lumen and do not allow for visualization of the aortic wall.[19] *In vivo* micro-MRI provides soft tissue contrast visualizing the aortic wall, but the typical through-plane distance is too coarse (order of magnitude 100–200 μm) for detailed 3D analyses.[9,20,21] Finally, 3D ultrasound offers a detailed in-plane pixel size (up to 15 μm) and through-plane distance (up to 35 μm) as well as limited soft tissue contrast, but it is a highly operator-dependent technique that is often subject to interpretation.[22] Differential phase contrast X-ray tomographic microscopy (PCXTM) uses synchrotron radiation to overcome all these limitations as it combines detailed soft tissue contrast (obtained through grating interferometry) with an isotropic pixel size of 6.5 μm.[23,24]

In this work, we validated PCXTM with PCXTM-guided histology to obtain a detailed insight into the global 3D morphology at specific locations of interest along dissecting AAAs. Combining these novel ultra-high resolution imaging techniques with *in vivo* imaging (ultrasound and micro-CT), we provide novel insight into the mechanism behind dissecting AAA formation, induced by combined angiotensin II infusion and anti-TGF-β antibody injection in C57BL/6J mice.

2. Methods

2.1 Sample size

Twenty manipulated animals and five controls were included in the *in vivo* imaging part of the study. Two animals died from other causes than transmural aneurysm rupture (found dead in the cage without haemoabdomen), and three animals did not respond to the treatment and did not develop any dissecting AAA. The priority criterion for PCXTM imaging was the macroscopic evidence of dissecting AAA after excision. A total of 20 animals (15 dissecting AAAs, 4 controls, and 1 non-responder) were imaged with PCXTM. Since the aim of the study was to describe the morphology of dissecting AAAs and not to compare a pre-defined effect in different groups, there was no group allocation within the aneurysmatic animals prior to data analysis. There were two experimental groups (dissecting AAAs and controls), and aneurysmatic animals were classified into different categories *a posteriori* based on morphological characteristics observed on the PCXTM scans. Subsequently, there was no need for randomization of the data or blinding during data analysis.

2.2 *In vivo* experiments

All the procedures were approved by the Ethical Committee of Canton Vaud, Switzerland (EC 2647.1) and performed according to the guidelines from Directive 2010/63/EU of the European Parliament on the protection of animals used for scientific purposes. Male C57BL/6J male mice were purchased at the age of 12 weeks from Janvier (Saint Berthevin, France). All manipulated mice ($n = 20$) were implanted a 200 μL osmotic pump (model Alzet 2004; Durect Corp., Cupertino, CA), filled with a solution of angiotensin II (Bachem, Bubendorf, Switzerland). Systemic neutralization of TGF-β was achieved by intraperitoneal injections of mouse anti-human TGF-β (2G7 clone, 20 mg/kg, three times a week). Dissecting AAA progression was longitudinally monitored at different time points *in vivo* using high-frequency ultrasound (Vevo 2100, VisualSonics, Toronto, Canada). Before sacrifice, six animals with obvious dissecting AAA presence (as confirmed on ultrasound) were injected intravenously in the lateral tail vein with 4 μL/g body weight of ExiTron nano 12 000 (Miltenyi Biotec, Bergisch Gladbach, Germany). These animals were subsequently scanned *in vivo* with a Quantum FX micro-CT scanner (Caliper Life Sciences, Hopkinton, MA, USA). During both ultrasound and micro-CT imaging, animals were anaesthetized by inhalation of 1.5% isoflurane. At the endpoints of the experiments, the mice were anaesthetized by ketamine/xylazine (100 and 15 mg/kg, respectively), and the sacrifice was resolved following the tissue collection.

2.3 *Ex vivo* experiments

After sacrifice, the aorta was flushed *in situ* by transcardiac perfusion of PBS (pH 7.4) through the left ventricle. In animals that died of transmural rupture of the aneurysmatic wall, the aorta was collected (without flushing) as soon as possible after finding them in the cage. The abdominal aorta of both intact and transmurally ruptured dissecting AAAs was carefully excised, and samples were fixed by immersion in 4% paraformaldehyde (PFA) in 0.15 mM PBS. The samples were scanned at the TOMCAT beamline of the Swiss Light Source, Paul Scherrer Institut, Villigen, Switzerland. All reconstructed data sets (*in vivo* as well as PCXTM) were semi-automatically segmented into 3D models using the commercial software package Mimics (Materialise, Leuven, Belgium). After PCXTM scanning, the samples were fixed as mentioned above, processed, and embedded in paraffin according to standard histological procedures. Four micrometre thick paraffin sections were carefully compared with the corresponding PCXTM images under a Leica DM750 bright field microscope to spot the exact rupture sites.

A more detailed description of the methods can be found in the Supplementary materials online.

3. Results

3.1 PCXTM—morphological imaging

We observed that two different phenomena led to the formation of an AAA-like geometry in angiotensin II-infused mice.

A first observation, invariably occurring in all aneurysmatic mice (15/15), was a mural tear of the tunica media that originated in the suprarenal segment near the ostium of the celiac artery. The medial tear ran in cranio-caudal direction over an average axial distance of 1.8 ± 1.1 mm. It was located either on the left side (6/15, *Figures 1C* and *3C*) or on the ventral side of the aorta (9/15, *Figures 2C*, *4C*, and *5D*). Tears on the left side extended from the cranial to the caudal side of the ostium of the celiac branch (*Figures 1C* and *3C*). Those on the ventral side of the aorta were most often located caudally to the ostium of the celiac branch (6/15, *Figures 2C* and *5D*), but they could also occur cranially (1/15) or extend both caudally and cranially (2/15, *Figure 4C*).

A second observation, occurring in the majority of aneurysmatic mice (13/15), was a local destruction and rupture of the medial architecture near the ostium of one or several small abdominal side branches. One to six ruptured branches were counted per specimen, and the affected branches were located either on the left (84% of all ruptured branches) or the dorsal side (16%) of the aorta. Almost all ruptures occurred in branches located cranially to the celiac artery (94%). Affected branches included the superior suprarenal artery, supplying blood to the left

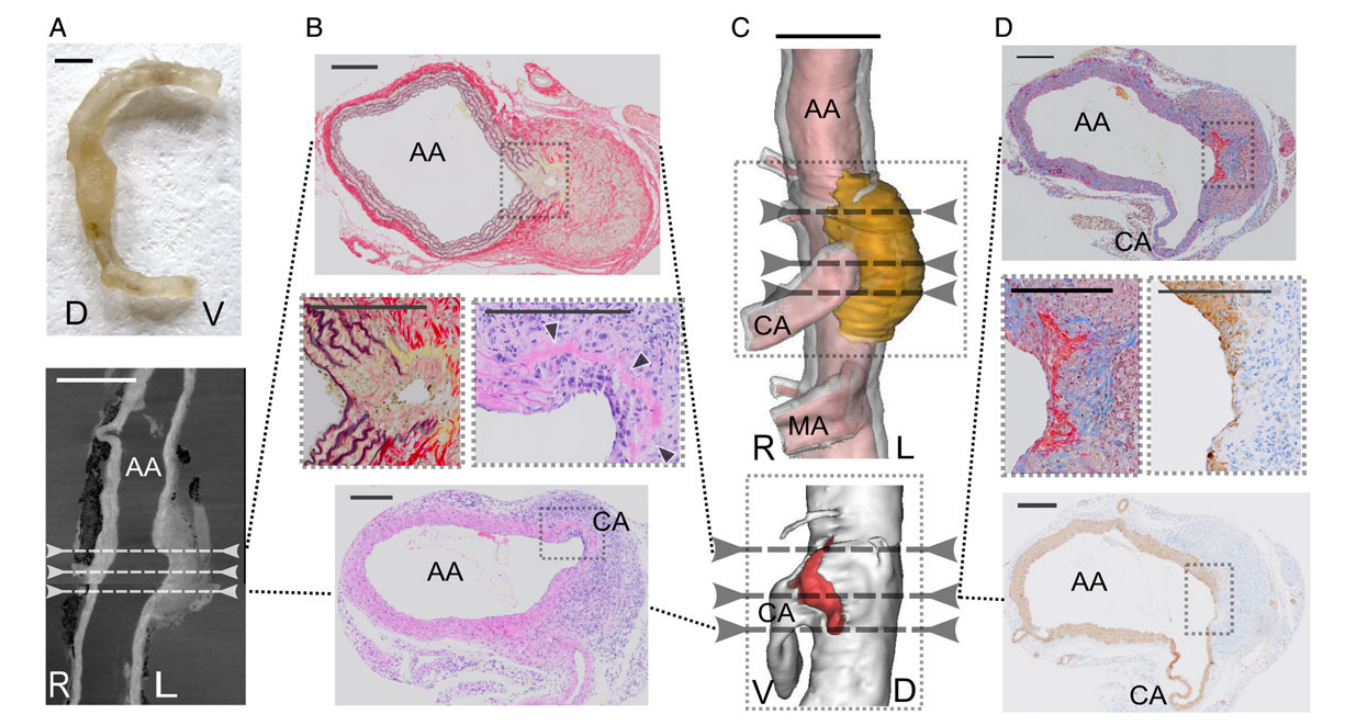

Figure 1 No intramural haematoma, 8 days after first detection on ultrasound. (*A*) Top: gross view of the dissecting AAA showing only a small dilation of the wall. Bottom: longitudinal PCXTM. Scale bar represents 1 mm. (*B*) PCXTM-guided histology. Top: PCXTM-guided combined Sirius Red (SR) and Miller stain shows destruction of the elastic lamellae and remodelled fibrotic adventitia. Bottom: H&E shows a haemostatic plug covering the tear while the intact adventitia prevents further blood extravasation. Scale bar represents 200 μm. (*C*) 3D representation based on PCXTM images. Tunica media in (transparent) white, intramural hematoma in orange, and blood-filled lumen in (transparent) red. The box shows the tear in the tunica media, on the left side of the celiac artery (tunica media in non-transparent white, blood-filled lumen in red, adventitia is hidden). Scale bar represents 1 mm (*D*) Top: Martius, Scarlet and Blue (MSB) stain shows the presence of fibrin (in red) within the haemostatic plug. Bottom: smooth muscle α-actin stain shows loss of smooth muscle cells, hence of medial architecture along the tear. Scale bar represents 200 μm. AA, abdominal aorta; R, right; L, left; D, dorsal; V, ventral; CA, celiac artery; MA, mesenteric artery.

adrenal gland, as well as various small abdominal branches and the most caudal of the intercostal arteries. Each of these mural ruptures led to an intramural haematoma dissecting the tunica media from the adventitia. Flow lines of alternated layers of blood cells and fibrin (Zahn's lines) were clearly discernible on the PCXTM images as alternating concentric layers around the vascular breach (*Figures 3A* and *5G*).

3.2 PCXTM—rupture site imaging

In six animals, which were scanned *in vivo* using contrast-enhanced micro-CT 2 h prior to sacrifice and aorta collection, the contrast agent (ExiTron) could be visualized on the PCXTM images as dense white aggregates. Due to the small size of the particles (diameter: 0.11 μm) and to the discontinuity of the intimal and medial layers, ExiTron entered the aortic wall together with erythrocytes (diameter: 6–7 μm) along the edges of the tear in the tunica media near the celiac artery and near the ruptured ostium of suprarenal and other abdominal side branches (*Figures 2A* and *4E*). Moreover, ExiTron also percolated into the tunica media near the ostia of intact intercostal arteries and abdominal side branches (2–10 affected branch ostia per specimen). Since the aortas were flushed after sacrifice, these areas indicate intra-vitam local increased permeability of the vessel due to disruption of the wall, with loss of the layered architecture (*Figure 2B*, top). The CD-31 stain showed focal hypertrophy of endothelium (endothelial activation), and the Haematoxylin and Eosin (H&E) stain showed widening of intercellular spaces and mild to moderate segmental thickening of the intima, due to accumulation of ExiTron, single apoptotic cells, and erythrocytes. Single erythrocytes (focal microhaemorrhages) and cellular debris were seen within the tunica media, while the adventitia was moderately infiltrated by leucocytes (*Figure 2B*, top).

3.3 Dissecting AAA initiation, progression, and rupture

The two main events influencing the final morphology were (i) the number of ruptured side branches and (ii) the location of the tear in the tunica media with respect to the intramural hematoma. The number of ruptured branches determined whether the intramural hematoma was non-existent, limited to the abdominal aorta, or extended into the thoracic aorta. The interaction between the tear in the tunica media and the location of the dissected adventitia determined whether a so-called false channel was formed or not. We chose to describe five different cases that illustrate how the interaction between the intramural haematoma and the medial tear influenced the final morphology of the dissecting AAAs.

3.3.1 Case 1: medial tear but no intramural haematoma, dissecting AAA restricted to the abdominal region

In a limited amount of samples, the tear in the tunica intima and media near the celiac artery, was the only observed lesion: supraceliac side

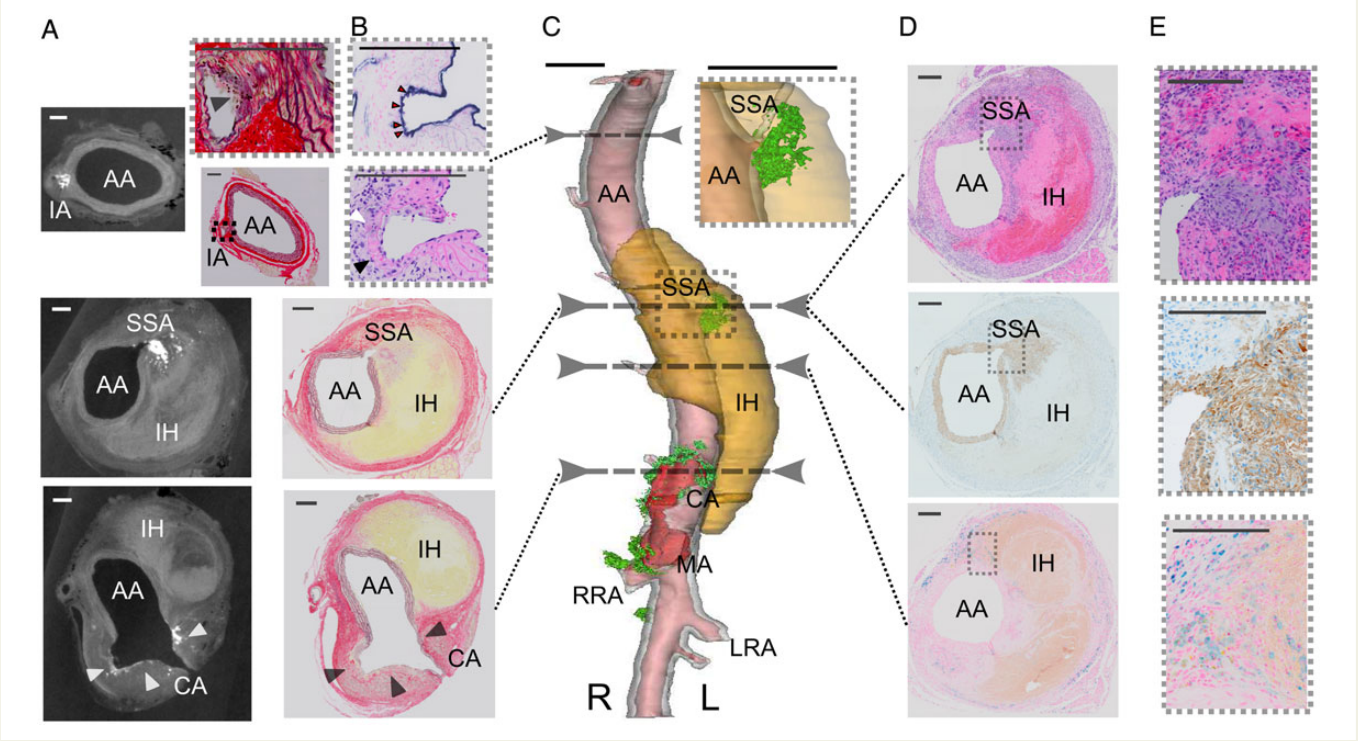

Figure 2 No false channel formation, 9 days after first detection on ultrasound. (*A*) Transversal PCXTM images. ExiTron aggregates near the ostium of an intact intercostal artery (top), near the ruptured ostium of the superior suprarenal artery (middle) and at the edges of the tear (indicated by arrowheads) in the tunica media (bottom). Scale bar represents 200 μm. (*B*) PCXTM-guided histology. Bottom left: combined SR and Miller stain at an intercostal artery. The vessel wall at the branch ostium (box, top left) shows loss of normal layered architecure and numerous cell debris (black arrow). The CD31 stain (box, top right) reveals endothelial cell hypertrophy (red arrowheads), while the H&E stain (box, bottom right) shows microhaemorrhages and single erythrocytes (black arrowhead), and cell debris (white arrowhead). Middle: the adventitia (in red) is dissected from the tunica media (in brown) due to an intramural haematoma (in yellow) caused by a rupture at the ostium of the superior suprarenal artery. Bottom: the dissected adventitia does not surround the tear in the tunica media (indicated by arrowheads). Scale bar represents 200 μm. (*C*) 3D representation based on PCXTM images. Tunica media in (transparent) white, intramural hematoma in (transparent) orange, blood-filled lumen in (transparent) red, ExiTron in green. Leaked ExiTron particles near the ruptured ostium of the superior suprarenal artery (box). The tear in the tunica media is located on the ventral side of the aorta, caudally to the celiac artery. No false channel is formed. Scale bar represents 1 mm. (*D* and *E*) Top: H&E stain shows how haematoma resorption, organization, and recanalization start from the luminal edges of the breach proceeding in a centrifugal manner. Middle: smooth muscle α-actin stain shows migrating spindle cells form the lumen into the plug and the haematoma. Bottom: Prussian Blue stain shows haemosiderophages aggregates infiltrating from the outer edges of the haematoma to resorb it. Scale bar represents 200 μm. SSA, superior suprarenal artery; IH, intramural haematoma; IA, intercostal artery; RRA, right renal artery; LRA, left renal artery.

branches remained intact (2/15, *Figure 1*). Along the tear, degeneration and rupture of elastic lamellae (*Figure 1B* top) and smooth muscle cells (*Figure 1D* bottom) occurred. The tear was covered by aggregated platelets and polymerized fibrinogen (fibrin) forming an haemostatic plug (*Figure 1B* bottom and *D* top). This was sufficient to avoid further leakage from the lumen and later on provided a scaffold for migration of endothelial cells to re-endothelialize the denudated vessel. Rapid blood flow in arteries and arterioles limited passive incorporation of erythrocytes within the plug.[25] Since no rupture of the superior suprarenal artery or any other abdominal branches occurred, the medial tear just led to a small suprarenal segmental expansion of the arterial wall without any intramural haematoma formation. This lesion would previously have been categorized as a Grade I aneurysm.

3.3.2 Case 2: medial tear and intramural haematoma without false channel formation, dissecting AAA restricted to the abdominal region

In most cases (13/15), the tear in the tunica intima and media near the celiac artery co-existed with the rupture of one or several small suprarenal abdominal branches. In 3/15 cases, the intramural haematoma was limited to the abdominal aorta while the tear in the tunica media was located on the ventral side of the aorta and caudally to the celiac artery (*Figure 2*). Since the intramural haematoma was occurring more cranially and leftwards, the adventitia was focally dissected from the media due to the haematoma while it remained intact in the area adjacent to the celiac tear (*Figure 2B* bottom). In this case, the intramural haematoma and the tear in the tunica media were two separate, independent events. Since the bleeding was focal, and no false channel was formed, it resulted in intramural blood accumulation. At the site of rupture, clotted blood was present (*Figure 2D* top) and 9 days after the event, progressive fibrin organization, spindle cells migration, and angiogenesis were evident and proceeded mostly in a centrifugal manner from the lumen (*Figure 2E*, top and middle). Haemosiderophages at the periphery of the haematoma (highlighted with Prussian Blue histochemical stain for iron, *Figure 2E* bottom) accounted for ongoing haematoma resorption. ExiTron particles that infiltrated the wall exhibited a typical grey-greenish discolouration of phagocytic cells[26] on the H&E stain (*Figure 2E* top). Over time, collagen was

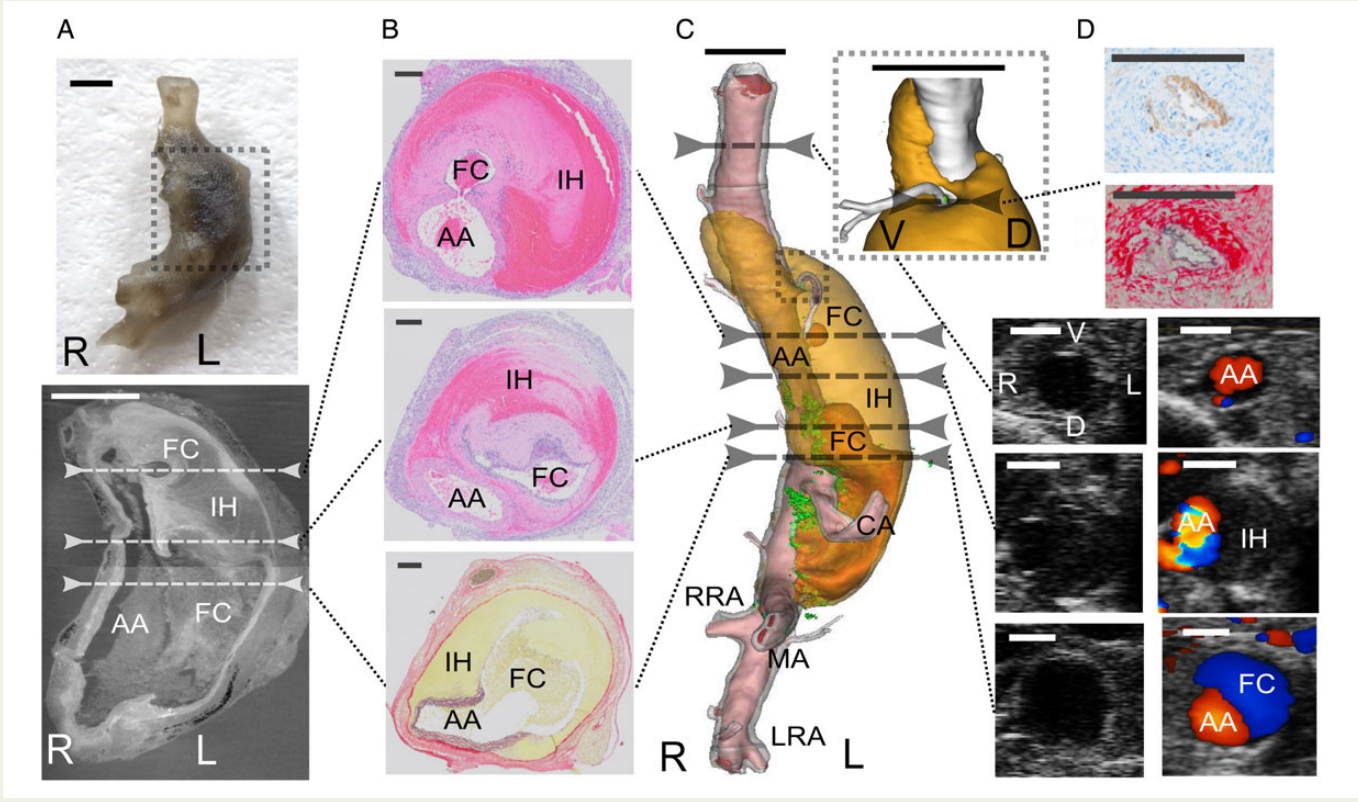

Figure 3 False channel formation, 2 days after first detection on ultrasound. (*A*) Top: gross view of the dissecting AAA. Bottom: longitudinal PCXTM. Scale bar represents 1 mm. (*B*) PCXTM-guided histology. Top: H&E stain at the ostium of the ruptured superior suprarenal artery. Middle: H&E showing the formation of the false channel into the haematoma. Bottom: combined SR and Miller stain. The haemorrhage caused by the tear in the tunica media is enclosed within the dissected adventitia. Scale bar represents 200 μm. (*C*) 3D representation based on PCXTM. Tunica media in (transparent) white, intramural hematoma in (transparent) orange, blood-filled lumen in (transparent) red, ExiTron in green. Scale bar represents 1 mm. (*D*) Top: the adventitial dissection is prevented to proceed further by a small abdominal branch with mural degeneration at its caudal end, as can be seen on the smooth muscle α-actin and combined SR-Miller stains. Scale bar represents 200 μm. Bottom: B-Mode (left) and Color Doppler (right) ultrasound. Blood flow towards the transducer in red, away from the transducer in blue. Apparent luminal dilation and retrograde (cranially directed) flow are present at the level of the tear in the tunica media, but not at the intramural haematoma. Scale bar represents 1 mm. FC, false channel.

deposited (most likely by migrating smooth muscle cells, myofibroblasts, and adventitial fibroblasts) at the rupture and haematoma sites (*Figures 1B top, 2B middle, 2B bottom, 3B bottom, 4D bottom*). These data support the contributing role of newly synthesized collagen to an intramural wound-healing response, as described earlier by Schriefl *et al.*[18]

3.3.3 Cases 3–4: medial tear and intramural haematoma with false channel formation, dissecting AAA restricted to the abdominal region

In 3/15 cases, the intramural haematoma was limited to the abdominal aorta and the dissected adventitia surrounded the tear in the tunica media (*Figures 3* and *4*). Depending on the amount of thrombus that was externally visible, these animals would previously have been categorized as Grade II or Grade III aneurysms. In one animal that was sacrificed 2 days after first detection of the dissecting AAA, a large tear in the tunica media ran on the left side of the celiac artery, extending both cranially and caudally of the latter (*Figure 3*). Along the length of the tear, blood flew out of the original lumen profile forming a large, focal apparent dilatation (*Figure 3A* and *C*). The haemostatic plug layering the dilated lumen was surrounded by clotted blood (*Figure 3B*). The latter was walled off by the adventitia, which had been dissected by the mural rupture of the tunica media near the ostium of the superior suprarenal artery (*Figure 3B*, top). The dilated lumen extended cranially into the haematoma, thus forming a false channel parallel to the original lumen (*Figure 3B*, middle). The dissection of the adventitia was stopped at the cranial end by a small branch that acted as a physical anchor point, inhibiting further peeling off of the adventitial layer (*Figure 3C*). The caudal aspect of the proximal segment of this branch was infiltrated by inflammatory cells (neutrophils and phagocytes), causing elastolysis and medial degeneration (*Figure 3D*, top).

In another animal that was sacrificed 10 days after first detection of a dissecting AAA on ultrasound, a small tear in the tunica media was located on the left side of the aorta, cranially to the celiac artery (*Figure 4*). In this case, blood was no longer flowing out of the 'real' lumen of the ruptured superior suprarenal artery as the small false lumen that was visible at this location in the younger dissecting AAA (*Figure 3A* bottom and *B* top) had been filled with fibrin and platelets (*Figure 4D* top). Consecutive 3D ultrasound showed *in vivo* how another false channel formed near the celiac artery over the course of several days (*Figure 4A*). The presence of free flowing blood in this false channel (but not in the more cranial part of the intramural haematoma) was confirmed by contrast-enhanced *in vivo* micro-CT and by Color Doppler images showing a counter-directional vortex forming with blood flowing in cranial direction (*Figure 4B*). The false channel was much smaller than the

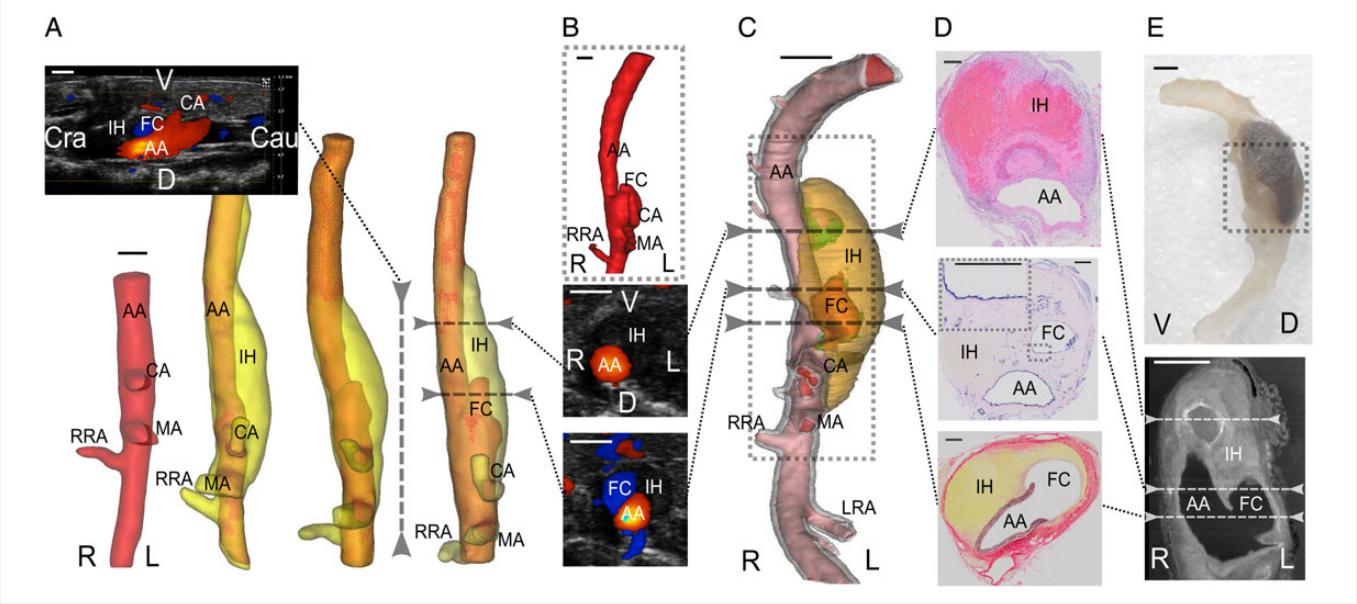

Figure 4 False channel formation, 10 days after first detection on ultrasound. (*A*) Modelling of the false channel into the haematoma over time. Reconstructed 3D ultrasound images acquired (from left to right) before dissecting AAA onset and 2, 6, and 10 days after first detection of dissecting AAA. Adventitia in (transparent) yellow and aortic lumen in red. Scale bar represents 1 mm. (*B*) Top: micro-CT just before sacrifice. Contrast-enhanced aortic lumen shown in red. Bottom: Color Doppler. Blood flow towards the transducer in red, away from the transducer in blue. Retrograde (cranially directed) flow in the false channel. Scale bar represents 1 mm. (*C*) 3D representation based on PCXTM images. Tunica media in (transparent) white, intramural hematoma in (transparent) orange, blood-filled lumen in (transparent) red, ExiTron in green. The tear in the tunica media is located on the ventral part of the aorta, cranial and caudal to the celiac artery. ExiTron has infiltrated around the rupture site of the superior suprarenal artery. The false channel has protruded cranially into the haematoma. Scale bar represents 1 mm. (*D*) PCXTM-guided histology. Top: H&E. The small false lumen at the ostium of the ruptured superior suprarenal artery (*Figure 4B*, top) has been obliterated by fibrin and platelets deposition, impeding blood flow. Middle: CD-31 shows endothelialization of the false channel by migrating endothelial cells from the breach edges. Bottom: combined SR and Miller stain. The haemorrhage resulting from the tear in the tunica media is enclosed within the dissected adventitia (intramural haematoma). Scale bar represents 200 μm. (*E*) Top: gross dissecting AAA. Bottom: longitudinal PCXTM. Scale bar represents 1 mm. Cau, Caudal; Cra, Cranial.

one in *Figure 3* and was restricted to the supraceliac region. Its borders were clearly delineated by endothelial cells that had migrated from the rupture site to re-endothelialize the surface of the plug, reducing its thrombogenicity (*Figure 4D* middle). The fibrin layer lining the false channel had become thinner, likely under the modelling effect of local blood flow forces (*Figure 4B bottom*).

3.3.4 Case 5: medial tear and intramural haematoma without false channel formation, dissecting AAA extending into the thoracic aorta

In 7/15 cases, the dissecting AAA was not restricted to the abdominal aorta but had a polymorphic shape that included the thoracic aorta (*Figure 5*). These aneurysms were previously categorized as Grade IV aneurysms. The polymorphic shape was directly related to the intramural rupture of additional branches. In total, 22 branches ruptured leading to intramural haematomas (with a maximum value of 6 per specimen) were counted on the PCXTM images in these dissecting AAAs, while only 12 ruptured branches (with a maximum value of 3 per specimen) were counted in the dissecting AAAs that were restricted to the abdominal aorta (8/15). Ruptured branches included small abdominal branches cranial to the celiac artery (such as the superior suprarenal artery, *Figure 5C*) and intercostal arteries (*Figure 5G* top). For none of the three cases depicted in *Figure 5*, a dissecting AAA was visible *in vivo* 2 days before sacrifice. Abdominal 3D ultrasound (*Figure 5A*), Color Doppler (*Figure 5A* and *B*), and micro-CT measurements (*Figure 5C*) confirmed there was no false channel formation, except for a small false lumen at the level of the ruptured superior suprarenal artery that could be observed on micro-CT (*Figure 5C*). The compression of the adventitia on its inner side, exerted by the large hematoma, caused separation of collagen fibres with multifocal loss of continuity of the layer and leakage of blood (*Figure 5E*) outside the vessel and into the abdomen (haemoabdomen).

3.3.5 Case 6: transmural rupture

Dissecting AAA transmural rupture occurred most often in dissecting AAAs extending into the thoracic aorta (5/6 lethal dissecting AAAs had a thoracic part, *Figure 6*). None of them could be imaged before transmural rupture had occurred (6/6 were found dead presenting internal bleeding). In the depicted case, the tear in the tunica media had propagated further cranially, connecting to the ostium of the ruptured superior suprarenal branch, which is clearly visible on the combined Miller and Sirius Red stain (*Figure 6B*, middle). The resulting haemorrhage led to a large intramural hematoma caudally to the tear near the celiac artery (*Figure 6A*, *B* bottom, and *C*). Multifocal disruption of the adventitia and perivascular soft tissues led to extravasation of blood into the abdominal space (*Figure 6B*, box) and most likely caused death of the animal by haemoabdomen.

4. Discussion

The possibility to image with soft tissue contrast at an isotropic pixel size of 6.5 μm makes PCXTM a powerful tool in preclinical

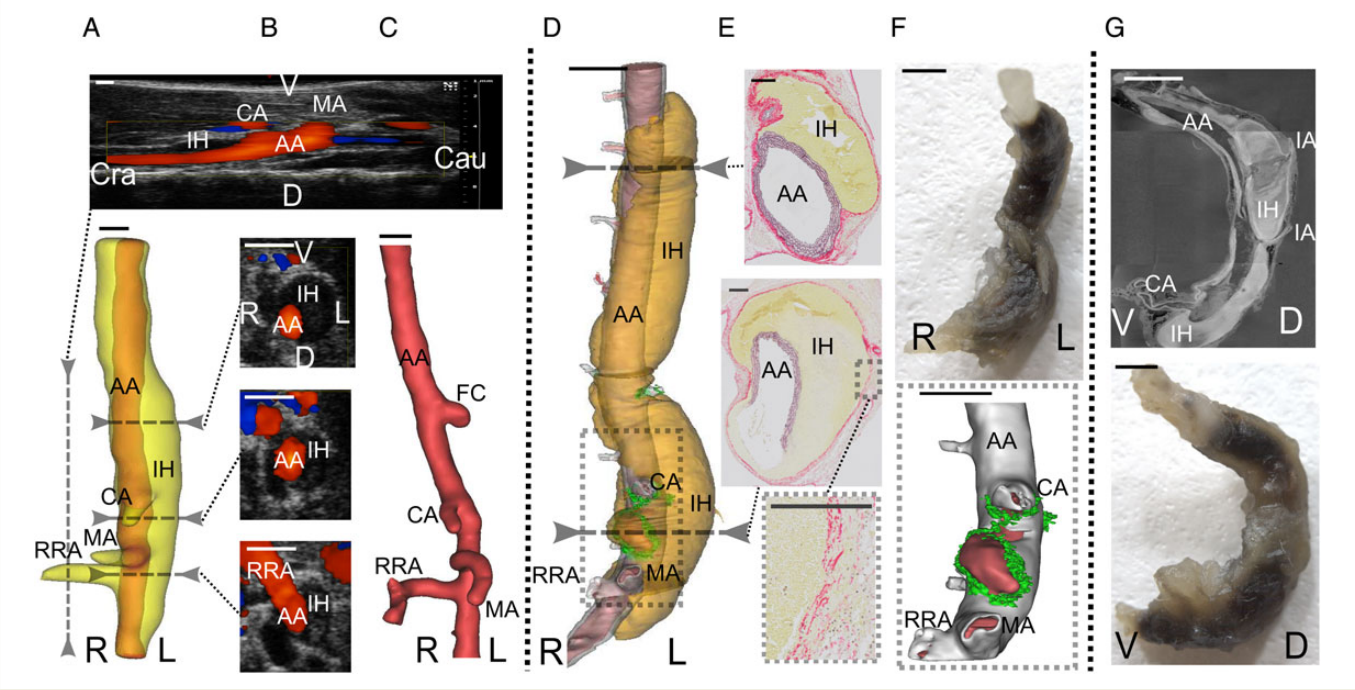

Figure 5 Three dissecting AAAs extending into the thoracic aorta. None of the shown dissecting AAAs was visible on ultrasound 2 days before sacrifice. (*A*) 3D ultrasound with remodelled adventitia in (transparent) yellow and lumen in red. Scale bar represents 1 mm. (*B*) Color Doppler. None of the imaged locations shows blood flow into the haematoma. (*C*) Contrast-enhanced micro-CT. No blood flow within the haematoma, except for a small false lumen near the ostium of the superior suprarenal artery. (*D*) 3D representation based on PCXTM images. Tunica media in (transparent) white, intramural haematoma in (transparent) orange, blood-filled lumen in (transparent) red, ExiTron in green. The tear in the tunica media (panel f, box) is located on the ventral part of the aorta, caudally to the celiac artery. Additional ruptured branches have led to a polymorphic dissecting AAA, with a focal narrowing at the level of the diaphragm. Scale bar represents 1 mm. (*E*) Combined SR and Miller stains. Top: at the cranial end an intact tunica media lies adjacent to the intramural haematoma that has dissected the tunica adventitia. An intact intercostal artery is visible. Bottom: the tear in the tunica media did not cause a significant dissection of the adventitia compared with the adjacent segment. In the box, the adventitia is compressed by the haematoma and separation of collagen fibres; hence, rupture of the tunica and further bleeding occur. Scale bar represents 200 μm. (*F*) Top: gross dissecting AAA corresponding to the 3D model in D. Bottom: zoomed area corresponding to the box in D. Scale bar represents 1 mm. (*G*) Top: PCXTM image showing the rupture at the caudal part of a dorsal intercostal artery, with concentric flow lines forming around the rupture. The progression of the dissection of the adventitia due to the haemorrhage is stopped by another intercostal artery. Bottom: gross dissecting AAA corresponding to the image on the top panel. Scale bar represents 1 mm.

cardiovascular research. Moreover, the validation of the greyscale images with PCXTM-guided histology (*Figure 2A* and *B*) allows for a much higher precision than what traditional, non-guided histology can offer. The exact location of rupture near the small branches (*Figures 2B* middle, *3B* top, *4D* top and *6B* middle), which had never been spotted with existing imaging techniques, could be cut and selected (before staining). Additionally, the 3D representation greatly facilitates the *a posteriori* interpretation of the 2D histological images. We have combined PCXTM-guided histology with *in vivo* imaging to visualize the mechanism behind pathogenesis and rupture of dissecting AAA in angiotensin II-infused mice. Despite the relatively small sample size, our data are the first to describe the large variation in morphology of these dissecting AAAs in an unequivocal way.

4.1 Hypothesis on dissecting AAA pathophysiology

Our data reveal an important role for small aortic branches on both initiation and expansion of dissecting AAAs. Mural ruptures near side branches are preceded by microscopic ruptures of elastic lamellae at branch ostia, as visualized by infiltrated ExiTron particles near the ostia of intact branches. These data confirm the results of Gavish *et al.*[27] who performed serial histology in angiotensin II-infused ApoE $^{-/-}$ mice to show that macrophage infiltration and transmedial breaks occur near the ostia of large abdominal side branches (celiac, mesenteric, and renals). A possible explanation for the important role of small branches lies in the typical flow patterns near the branch ostia, where zones of flow recirculation create local areas of low shear stress.[19,28,29] This might lead to endothelial dysfunction with or without denudation, followed by increased binding and eventually transmigration of marginalized leucocytes. As in the pathogenesis of atherosclerosis, hyperlipidaemia (and especially hypercholesterolaemia) might lead to intimal accumulation of lipoproteins, which in turn could be oxidized and exert a pro-inflammatory, chemo-attractant action on monocytes/macrophages.[30,31] Moreover, the abrupt change in the number of medial lamellae from the larger aorta to the smaller side branch may induce a locally different reaction to these haemodynamic forces,[27,32] and the mechanical tension exerted by the branch on the tunica media is locally increased at the point of attachment.[33]

The upstream formation of a false channel into a previously existing haematoma over the course of several days (*Figure 4*) is confirmed when re-interpreting previously published transversal micro-MRI images[21] and

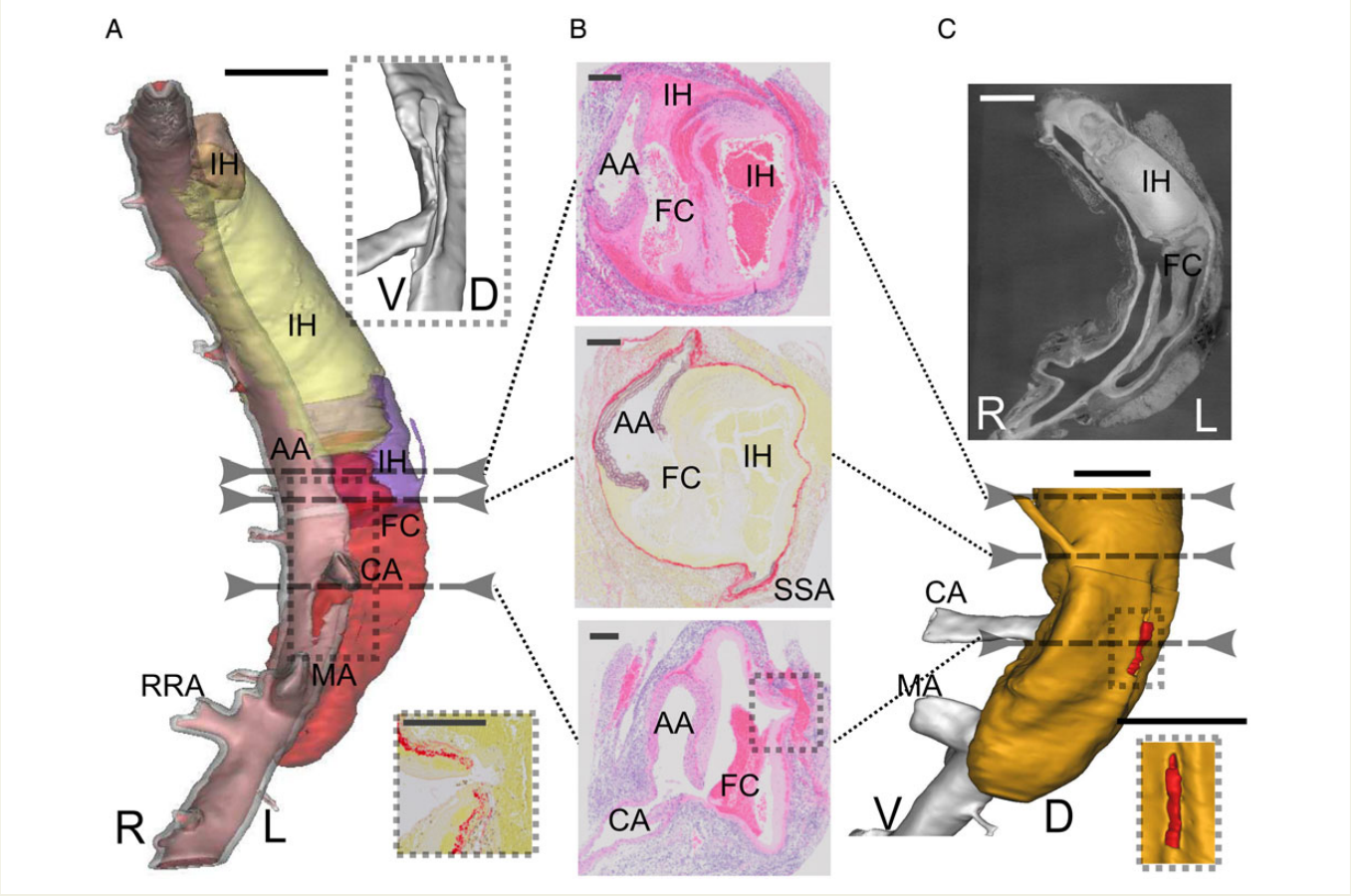

Figure 6 Transmural dissecting AAA rupture. (*A*) 3D representation based on PCXTM. Tunica media in (transparent) white, blood-filled lumen in (transparent) red, intramural haematomas related to different ruptured branches in (transparent) blue, yellow, and brown. Scale bar represents 1 mm. (*B*) PCXTM-guided histology. Top: H&E. The false channel caused by the tear pushes a second haematoma caused by the ruptured superior suprarenal artery outwards. Middle: rupture in the elastic lamellae near the ostium of the superior suprarenal artery. Bottom: multifocal disruption of the adventitia and perivascular soft tissues (box) lead to extravasation of blood into the abdominal cavity (haemoabdomen). Scale bar represents 200 μm. (*C*) Top: longitudinal PCXTM. Bottom: 3D representation based on PCXTM. A tear in the adventitia (shown in orange) can be seen on the dorsal side of the celiac artery (box). Scale bar represents 1 mm.

is even more pronounced after CNA-35 injection to enhance collagen visibility.[9] It is also confirmed by previously published Color Doppler data, both in the presence[8,9] or absence[4,22] of anti-TGF-β blockade. We hypothesize that false channel formation (*Figures 3* and *4*) is related to the fact that in these animals the adventitia (which initially protected the haemostatic plug as in *Figures 1* and *2*) was dissected by the intramural haematoma. The plug was thus subjected to an intramural pressure difference between the high (arterial) pressure on its luminal side and the low pressure on its outside, exerted by the haematoma. If the fibrin and platelets mesh layer could resist to the initial sudden pressure difference by virtue of its elasticity, they remodelled and were pushed in cranial direction towards the haematoma, thus forming a false channel (*Figures 3C* and *4C*). On the other hand, if the haemostatic plug could not withstand the luminal pressure, blood flowed from the arterial lumen into the haematoma with a much higher volume than what was the case in haematomas caused by mural ruptures near small suprarenal branches. This increased the severity, hence the size of the haematoma with a significant stress on the adventitial layer causing the latter to rupture (*Figure 6B* and *C*). This hypothesis also implies that the tear in the tunica media near the celiac artery preceded the ruptures at the lumen of small suprarenal branches, which is supported by the existence of dissecting AAAs with a tear and haemostatic plug, but without intramural thrombus (*Figure 1*).

4.2 A paradigm shift? Comparison with literature

At first sight, our data seem to contradict the existing paradigm in AAA research in mice: luminal expansion has been observed or implicitly supported in many papers, while suprarenal branch ruptures have not. However, when taking a closer look at the actual figures in literature on which the existing paradigm has been built, none of them contradict and most of them explicitly support our novel observations and interpretations.

An increase in luminal AAA diameter is usually based on quantification of transversal B-Mode ultrasound images, taken at the level of the 'maximal diameter'.[13,15,32,34–38] Most papers do not show any of the B-Mode images that were used for diameter quantification,[13,15,32] but the available images can be categorized into two different types: some clearly demonstrate a concentric dilatation of the aortic diameter,[36–38] whereas others visualize an asymmetric distribution of two distinct

regions within the circular cross-section.[34,35,39] Both types were reproduced by our B-Mode ultrasound. In those cases where B-Mode and Color Doppler images showed an almost concentric, blood-filled, dilated aorta (*Figures 3D* bottom and *4B* bottom), PCXTM and PCXTM-guided histology invariably showed a tear in the tunica media (*Figures 3A* bottom, *B* bottom, *4B* bottom and *4D* bottom). This was confirmed by a vast amount of literature: wherever a luminal expansion is visible on histology, it coincides with a tear in the tunica media.[3–9,18,27,29,32,34,36,37]

At most locations, however, the cross-section on our B-Mode images was partly filled by a grey, speckled (*Figure 3D* middle) or sometimes black (*Figure 5B* top) region, similar to what had been reported before.[34,35] Color Doppler revealed that at these locations blood flow remained within the original aortic lumen (*Figures 3D* middle, *4B* middle, and *5B*), which was confirmed *in vivo* by contrast-enhanced micro-CT (*Figures 4B* and *5C*). At these regions, PCXTM and PCXTM-guided histology invariably showed a non-dilated lumen in an intact tunica media adjacent to an intramural haematoma (*Figures 2B* middle, *3B* top, *4D* top, and *5E* top). We therefore speculate that the diameter value that was used to quantify 'luminal expansion' with ultrasound should in most cases be re-interpreted as an expansion of the outer wall of the tunica adventitia due to formation of an intramural haematoma. The lack of true luminal dilatation in some of the dissecting AAAs has been confirmed by *in vivo* micro-CT[19,29] and MRI,[21,40–42] and almost all papers include histology images of an intact aortic media adjacent to an intramural region.[3–9,18,27–29,31–34] The only difference is that in these cases the intramural region was often termed a 'remodelled adventitia' or 'thrombus' and when it was termed a haematoma, its source was not identified. We are the first to relate the intramural haematoma to additional ruptures near suprarenal branches.

4.3 Limitations and conclusions

At this stage, our observations are limited to C57BL/6J mice undergoing simultaneous angiotensin II infusion and systemic neutralization of TGF-β. These mice have been reported to have a higher incidence of Grade IV, polymorphic AAAs and to succumb more often due to transmural dissecting AAA rupture than the more commonly used angiotensin II-infused ApoE$^{-/-}$ mice.[8] This explains why in the current study animals were sacrificed at a relatively early stage of dissecting AAA formation, and why 7 out of the 15 observed dissecting AAAs extended into the thoracic aorta. Despite the fact that literature data (from histology,[4,18,27] ultrasound,[34,35,39] micro-CT,[19,29] and MRI[21,40–42]) seem to suggest that dissecting AAAs in the angiotensin II-infused ApoE$^{-/-}$ mouse model suffer from a similar pathophysiology, this cannot be deduced from the current data. Similarly, any conclusions on human AAA formation would be premature. Moreover, due to the strong competition for PCXTM beam time, and due to the relatively large size and hence long scan time of murine dissecting AAAs, the number of included samples and investigated time points was rather limited. We therefore aim to confirm our findings in a larger sample of angiotensin II-infused ApoE$^{-/-}$ mice, using PCXTM and PCXTM-guided histology to focus on both earlier time points (before any tear or rupture is present) and later time points (after haematoma remodelling). More research is also needed to investigate to what extent our findings have implications on the early stages of human AAA formation and/or vascular dissection.

In conclusion, we demonstrated how PCXTM and PCXTM-guided histology can lead to novel insights in cardiovascular pathology in mice. We visualized macroscopic and microscopic ruptures (both in 2D and 3D) near suprarenal branches in the tunica media of C57BL/6J male mice that were subjected to angiotensin II infusion and systemic neutralization of TGF-β. We demonstrated how these ruptures lead to apparent luminal dilatation and intramural haematoma formation, and provided an explanation for both the observed variability in shape and the predilection for the left suprarenal aorta of angiotensin II-induced dissecting AAAs in mice.

Supplementary material

Supplementary material is available at *Cardiovascular Research* online.

Acknowledgements

The authors thank Orestis Vardoulis and Iraklis Kourtis for their assistance during the PCXTM scans. Further we acknowledge Agnès Hautier and the entire team of the Histology Core Facility at the Ecole Polytechnique Fédérale de Lausanne (EPFL) for their technical expertise with the PCXTM-guided histology, and Dr José Artacho from the Bioimaging and Optics platform (PTBIOP) at EPFL for his expert help with the image data processing. We also thank Marion Varet and the entire team of the Phenotyping Unit in the Center of PhenoGenomics at the school of Life Sciences in EPFL for their technical and scientific expertise in the micro-CT experiments, Dr Bert Vandeghinste at IBiTech-Medisip at Ghent University for his help with the micro-CT reconstructions, and Prof. Julie De Backer at Ghent University and Prof. Peter Davies at the University of Pennsylvania for their valuable feedback on the manuscript.

Conflict of interest: none declared.

Funding

This research was funded by the Special Research Fund of Ghent University and by internal funds of the Laboratory of Hemodynamics and Cardiovascular Technology, EPFL. B.T. received a travel grant of the Flemish Fund for Scientific Research, and R.F.A-S. received a grant of the Novartis Consumer Health Foundation.

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